Recent Achievements Regarding Heat Release and Temperatures during Fires in Tunnels

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ABSTRACT

The paper presents an overview of the latest available information about heat release rate (HRR) and gas temperature development in tunnels. Results from major fire test series in tunnels are presented, as well as fire tests with vehicles in other type of applications. The HRR and temperature development from the large-scale fire tests performed in the Runehamar tunnel in 2003 is presented. These tests included four tests with different HGV trailer fire loads. Heat release rate over 200 MW and gas temperatures over 1300 ^{o}C were measured.

1. INTRODUCTION

A number of tunnel fires have occurred throughout Europe with catastrophic outcome. In these fires the production of heat, smoke, and toxic fumes played a major role for the outcome. The main reason being that the vehicles contain a very high fire load and that the fire could easily spread. The heat production, or the heat release rate (HRR) and the gas temperature in the vicinity of the fire, is used for design of safety systems and tunnel linings. This involves time dependent curves of HRR and gas temperatures, respectively, but these curves are not always interconnected in the designing process. In this paper an overview of available experimental data on HRR for vehicles and peak gas temperatures in the vicinity of the fire source is given. Among these experiments are the large-scale tests in the Runehamar tunnel in 2003 [1,2].

2. OVERVIEW OF LARGE-SCALE TUNNEL EXPERIMENTS

The first extensive large-scale test series where the HRR and gas temperatures from various large vehicles (passenger cars, train wagons, subway cars, and HGV trailer) were measured was in the EUREKA 499 –FIRETUN test series in 1990 to 1992 [3]. The peak HRRs measured varied between 6 and 128 MW and the gas temperatures at ceiling above the vehicles between 200 ^{o}C and 1100 ^{o}C. The final results and all the detailed information from the project were presented in a technical report published in 1995 [3]. Another major series of fire test in tunnels was performed in the Memorial Tunnel in Massachusetts in 1995 [4]. However, the fire load in this test series did not consist of vehicles. It consisted of liquid pool fires of different sizes varying between 20 and 100 MW and gas temperatures at the ceiling did not exceed 1100 ^{o}C. The main purpose was to investigate the effects of different ventilation systems on the smoke control in tunnels. Other important test series include the one in the Offenegg tunnel (Switzerland,1965) using petrol pools from 6.6 to 95 m^2 [5], the Zwenberg tunnel (Austria, 1975) [6] using petrol pool fires from 6.8 to 13.6 m^2, and the P.W.R.I. experiments (Japan, 1980) using pool fires of 4 and 6 m^2, passenger cars and buses. No HRR measurements were performed in these tests. In the Ofenegg tunnel tests gas temperatures up to 1200 ºC were measured. In the Netherlands, small-scale tests using petrol pans were performed in an 8 m long tunnel, 2 m high and 2 m wide [7]. In these tests gas temperatures in the range of 900 – 1360 ºC were measured. The Rijkswaterstaat Tunnel Curve (the RWS Curve) in the Netherlands is based on these tests. The RWS curve represents a worst-case scenario of a 300 MW petrol tanker burning in a tunnel for two hours.

In year 2002, a test series was performed in the in the Second Benelux tunnel [8] in the Netherlands. HRR and temperatures from pan fires (5, 20 MW), vehicle fires such as passenger cars, vans and semi-trailer fire load were measured. The peak HRR (based on weight loss) varied between 4.5 and 26 MW and the maximum gas temperatures in the ceiling did not exceed 600 ºC.

In 2003 large-scale tunnel tests were carried out with semi-trailer cargos in the Runehamar tunnel in Norway [1, 2]. The tunnel is a 1600 m long two-way-asphalted road tunnel that was taken out of use. It is 6 m high and 9 m wide, with a slope varying between 1-3 %. In total four tests were performed with fire in a semi-trailer set-up. In three tests mixtures of different chosen cellulose and plastic materials were used, and in one test "real" commodity consisting of furniture and fixtures was used. In all tests the mass ratio was approximately 80 % cellulose and 20 % plastic. A polyester tarpaulin covered the cargo. The maximum heat release rates varied between 70 MW and 203 MW. The maximum gas temperatures varied between 1250 ºC and 1365 ºC.

3. OVERVIEW OF EXPERIMENTAL DATA

3.1 Heat release rate

Road vehicles

The literature describes a number of measurements of HRRs of road vehicles. In Table 1 a summary of these tests is given. The HRRs for single passenger cars (small and large) vary from 1.5 to 8 MW, but the majority of the tests show HRR values less than 5 MW. When two cars are involved the peak HRR vary between 3.5 and 10 MW. There is a great variety in the time to reach peak HRR. It varies between 10 and 55 minutes. Based on the data presented here, one can observe a tendency that peak HRR increase linearly with total calorific value of the passenger cars involved in the fire. An analysis of all data available shows that the average increase is about 0.7 MW/GJ. This is an interesting observation since a French study has showed an increase of cars calorific potential versus years [12]. As there appears to be a trend for new cars to release more energy than older ones, designers of tunnel safety must consider this when deciding on a design fire rating. The number of passenger cars involved is also an important factor to consider in the design.

There are not many bus tests performed. The two tests shown in the Table 1 indicate that the peak HRR is in the order of 30 MW and the time to reach peak heat release rate is less than ten minutes. The highest peak HRRs are obtained for the HGV trailers. It is found to be in the range of 13 to more than 200 MW depending on the fire load. The time to reach peak HRR is in the range of 10 to 20 minutes. The fire duration is less than one hour for all the HGV trailer tests presented in Table 1. In Figure 1 time-resolved HRR curves are given for the tests presented in Table 1.

Table 1 Large scale experimental heat release data on road vehicles.

Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	Calorific value (GJ)	Peak HRR (MW)	Time to peak HRR (min)	Reference
Passenger Cars				
Three tests with ordinary passenger cars manufactured in the late 1970s	4	1.5, 1,8 and 2	12, 10 and 14	Mangs and Keski-Rahkonen [9]
Renault Espace J11-II manufactured in 1988, EUREKA 499, u= 0.4 m/s	7	6	8	Steinert [10]
Citroën BX 1986	5	6	15	Shipp and Spearpoint [11]
Austin Maestro 1982	NA	8.5	16	Shipp and Spearpoint [11]
Opel Kadett 1990 ; Second Benelux tests, test 6 and 7, u = 0 and 6 m/s	NA	4.8 and 4.7	11 and 38	Lemair et al [8]
Tests with single cars manufactured in the 80s and 90s (Peugeot, Renault, Citroen, Ford, Opel, Fiat, VW)	2.1, 3.1, 4.1 and 6.7	3.5, 2.1, 4.1 and 8.3	10, 29, 26 and 25	Joyeux [12]
Tests with one car (Trabant, Austin and Citroen)	3.1, 3.2 and 8	3.7, 1.7 and 4.6	11, 27, 17	Steinert [13]
Tests with two cars manufactured in the 80s and 90s (Peugeot, Renault, Citroen, Ford, Opel, Fiat, VW)	8.5, 7.9, 8.4 and NA	1.7, 7.5, 8.3 and 10	NA, 13, NA, NA	Joyeux [12]
Test with two cars (Polo+Trabant, Peugeot+Trabant, Citroen+Trabant, Jetta+Ascona)	5.4, 5.6, 7.7 and 10	5.6, 6.2, 7.1 and 8.4	29, 40, 20 and 55	Steinert [13]
Tests with three cars (Golf + Trabant+Fiesta)	NA	8.9	33	Steinert [13]
Buses				
A 25-35 year old 12 m long Volvo school bus with 40 seats, EUREKA 499, u=0.3 m/s	41	29	8	Ingason et al [14]
A bus test in the Shimizu Tunnel, u=3-4 m/s	NA	30 *	7	Kunikane et al [15]
HGV trailers				
A trailer load with total 10.9 ton wood (82%) and plastic pallets (18%), **Runehamar** test series, Test 1, u=3 m/s	240	203	18	Ingason and Lönnermark [1]
A trailer load with total 6.8 ton wood pallets(82%) and PUR mattrasses (18%), **Runehamar** test series, Test 2, u=3 m/s	129	158	14	Ingason and Lönnermark [1]
A Leyland DAF 310ATi – HGV trailer with 2 tons of furniture, EUREKA 499, u= 3-6 m/s	87	128	18	Grant and Drysdale [16]
A trailer with 8.5 ton furnitures, fixtures and rubber tyres, **Runehamar** test series, Test 3, u=3 m/s	152	125	10	Ingason and Lönnermark [1]
A trailer mock-up with 3.1 ton corrugated paper cartons filled with plastic cups (19%**), **Runehamar** test series, Test 4, u=3 m/s	67	70	14	Ingason and Lönnermark [1]
A trailer load with 72 wood pallets, Second Benelux tests, Test 14, u=1-2 m/s	19	25	12	Lemair et al [8]
A trailer load with 36 wood pallets, Second Benelux tests, Test 8, 9 and 10, u=0, 4-6 m/s and 6 m/s	10	13, 19 and 16	16, 8 and 8	Lemair et al [8]
A Simulated Truck Load (STL), EUREKA 499, u=0.7 m/s	63	17	15	Ingason et al [14]

NA=Not Available
* This is estimated from the convective HRR of 20 MW derived by Kunikane et al [15] because a sprinkler system was activated when the convective HRR was 16.5 MW. It is assumed that 67 % of the HRR is convective and thereby the HRR = 20/0.67=30 MW.
** mass ratio of the total weight

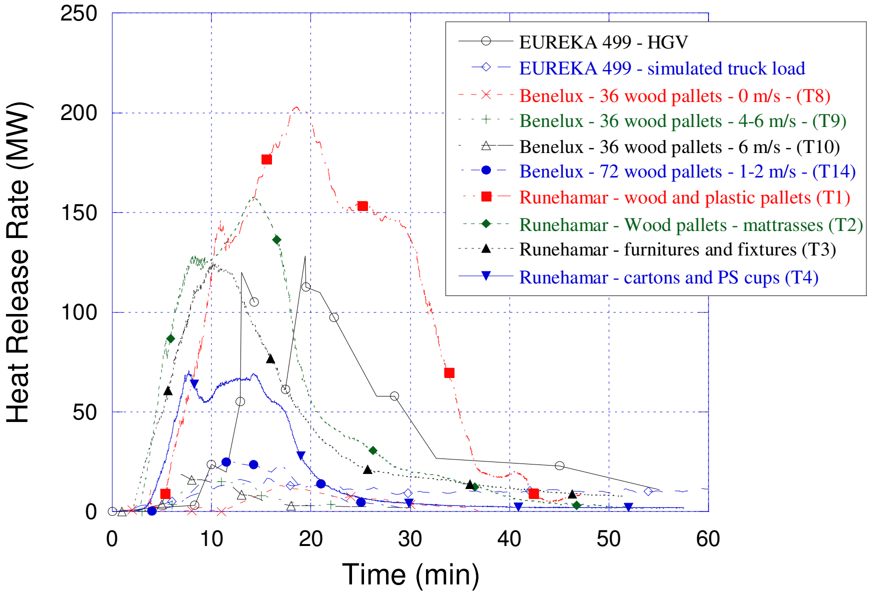

Figure 1 The HRR for the HGV trailer tests presented in Table 1.

The interaction between the ventilation flow and HRR of HGV trailer fire loads has been investigated by Carvel et al. [17]. They found that the heat release rate of a HGV could increase in size by a factor of four for a ventilation flow rate of 3 m/s and by factor of ten at 10 m/s. They also found that the fire growth rate could increase by a factor of five for 3 m/s and by factor of ten for 10 m/s. A Bayesian probabilistic approach was used to refine estimates, made by a panel of experts, with data from experimental fire tests in tunnels. Recently, the expectation curves were revised [18] including data also from the tests in the Second Benelux tunnel [8] and the Runehamar tunnel [1]. Now the HRR increases with a factor five at 3 m/s and a factor of 20 to 25 at 10 m/s for a one lane tunnel compared to natural ventilation during the growth phase. The corresponding factors for a two lane tunnel is around 4 and 6, respectively. For fully involved HGV fires, the factors for one lane tunnels are 4 at 3 m/s and 8 at 10 m/s while they for two lane tunnels are approximately 1.9 and 3, respectively. However, their conclusions were still based on rather limited experimental data and there is a need for experimental work to validate these results.

The Second Benelux tests with the 36 wood pallet fire load show that the fire development rate with ventilation was 1.7 to 2 times faster than the fire development without ventilation. The peak heat release rate was 13.5 MW without ventilation, 19 MW with 4-6 m/s ventilation and 16.5 MW with 6 m/s, which corresponds to 1.4 and 1.2 times higher, respectively. The peak heat release rate with 72 wood pallets was 26 MW and the fire growth rate was about 1.5 times faster than the 36 wood pallet fire load and no ventilation. In conclusion one can note that the fire growth rate was not more the 2 times higher and the peak heat release rate not more than 1.4 times higher compared to test with no longitudinal ventilation. These results do not comply very well with the results obtained by Carvel et al. [17, 18].

Rail and metro vehicles

The literature describes very few measurements of HRRs for rail and metro vehicles. The majority of the tests available are from EUREKA 499 test series. In Table 2 a summary of these tests is given. The test results presented in Table 2 are mainly based on single coaches. The peak HRR is found to be in the range of 7 to 43 MW and the time to reach the peak HRR varies from 5 to 80 minutes. If the fire were to spread between the train coaches, the total HRR and the time to reach peak HRR would be much higher than the values given here although the HRR for each coach cannot be summed up. This is because the first coach would not necessarily reach the peak HRR at the same time as the later ones. The EUREKA 499 tests show that there are many parameters that will affect the fire development in a train coach. These include the body type (steel, aluminium etc), the quality of the glazed windows, the geometry of the openings, the amount and type of combustible interior and its initial moisture content, the construction of wagon joints, the air velocity within the tunnel and the geometry of the tunnel cross-section. These are all parameters, which needs to be considered in a design process of a rail- or metro tunnel.

Table 2 Large scale experimental heat release data on rail vehicles

Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	Calorific value (GJ)	Peak HRR (MW)	Time to peak HRR (min)	Reference
Rail				
A Joined Railway car; two half cars, one of aluminium and one of steel, EUREKA 499, u=6-8/3-4 m/s	55	43	53	Steinert [10]
German Intercity-Express railway car (ICE), EUREKA 499, u=0.5 m/s	63	19	80	Steinert [10]
German Intercity passenger railway car (IC), EUREKA 499, u=0.5 m/s	77	13	25	Ingason et al [14]
British Rail 415, passenger railway car[a)]	NA	16	NA	Barber et al. [19]
British rail Sprinter, passenger railway car, fire retardant upholstered seatings[a)]	NA	7	NA	Barber et al. [19]
Metro				
German subway car, EUREKA 499, u=0.5 m/s	41	35	5	Ingason et al [14]

a) The test report is confidential and no information is available on test set-up, test procedure, measurement techniques, ventilation, etc.

A new standard for materials and components in railway vehicle is available in a preliminary version [20]. This will regulate the fire behaviour materials used, *e.g.* in seats and linings. It will, however, not regulate or give guideline on the effects of the peoples clothing and luggage etc, temporarily being inside a railway wagon. Examples of when this can have affected the result of real fires are the Daegu subway fire, South Korea in 2003 and the fire in funicular train coach near Kaprun, Austria in 2000. This can increase the fire load and will especially affect the early development of the fire.

A very important factor for the development of the fire is the quality and mounting of the windows. As long as the windows do not break or fall out (and there are no other large openings), the fire develops slowly. On the other hand, when the windows break the fire can spread and increase in intensity very quickly.

3.2 Temperatures

There are number of temperature-time curves available for design of load bearing constructions in buildings and underground constructions. The most common is the standard curve used in laboratory testing, *e.g.* ISO 834. This curve represent materials found in buildings and is not really relevant for tunnels, mainly because of slower temperature rise that has been found from tunnel experiments. ISO 834 has been used in many countries for tunnels, but rather soon it was clear that it did not represent all materials, *e.g.* petrol, chemicals etc. and therefore a special curve, the hydrocarbon curve (the HC-curve) was developed in the 1970s. It has mainly been used in the petrochemical and off-shore industries but it has also started to be used for tunnels. The main difference between these two curves is the faster development and peak temperature rise. Special temperature curves have been developed in some countries to simulate hydrocarbon fires in tunnels. Examples of such curves are the RABT/ZTV Tunnel Curve in Germany, modified HC_{inc} in France, and the

Rijkswaterstaat Tunnel Curve (the RWS Curve) in the Netherlands. These tunnel curves are often used, but are not required by all authorities or tunnel owners. One reason for this situation is that these extreme situations often are thought to be found only in connection with for example a tanker fire; another reason is the lack of measurements in real scale fires, *e.g.* in fires in HGV trailer. There are a number of large-scale tests available with gas temperatures in the vicinity of the fire source. In Table 3 and Table 4, a summary is presented of the peak ceiling gas temperatures in the vicinity of the fire source for different tunnel tests (only large fires such as petrol fires, diesel fires and large vehicle fires in tunnels).

Table 3 Peak gas temperatures measured in large scale road tunnel fire experiments

Type of fuel, test series, test nr, u=longitudinal ventilation m/s, A=cross-section m^2	HRR (MW)	Peak gas temperature (ºC)	Reference
Liquid pan			
Pans with petrol (appr 4 m^2 - 1500 litre), TNO small scale tests, A=4 m^2	NA	1360	TNO report [7]
Pans with petrol (47.5 m^2), Ofenegg tunnel serie, u=0 – 1.7 m/s, A=23 m^2	NA	1310	Test report Ofenegg Tunnel [5]
Liquid pans, Memorial tunnel tests, u=0 m/s, A=36 m^2	50	1090	Test report Memorial Tunnel [4]
Pans with petrol (6.6 m^2), Ofenegg tunnel serie, u=0-1.7 m/s, A=23 m^2	NA	1030	Test report Ofenegg Tunnel [5]
Pans with petrol (95 m^2), Ofenegg tunnel serie, u=0-1.7 m/s, A=23 m^2	NA	1025	Test report Ofenegg Tunnel [5]
Liquid pans (45 m^2), Memorial tunnel tests, u=0 m/s, A=60 m^2	100	870	Test report Memorial Tunnel [4]
Liquid pans (45 m^2), Memorial tunnel tests, u=3 m/s, A=60 m^2	100	700	Test report Memorial Tunnel [4]
Pans with 60% heptane and 40% toluene (7.2 m^2), Second Benelux tests, Test 3a and 3b, u=1.7 and 5 m/s, A=50 m^2	12	470 and 250	Lemair et al [8]
Passenger cars			
Renault Espace J11-II manufactured in 1988, EUREKA 499, u= 0.4 m/s, A=25 - 35 m^2	6	480	Eureka report [3]
Opel Kadett 1990 ; Second Benelux tests, test 6 and 7, u = 0 and 6 m/s, A=50 m^2	4.8 and 4.7	210 and 110	Lemair et al [8]
HGV trailer			
A trailer load with total 10.9 ton wood (82%) and plastic pallets (18%), **Runehamar** test series, Test 1, u=3 m/s, A=50 m^2	203	1365	Lönnermark and Ingason [2]
A trailer load with total 6.8 ton wood pallets(82%) and PUR mattrasses (18%), **Runehamar** test series, Test 2, u=3 m/s,A=50 m^2	158	1282	Lönnermark and Ingason [2]
A trailer with 8.5 ton furniture, fixtures and rubber tyres, **Runehamar** test series, Test 3, u=3 m/s, A=50 m^2	125	1281	Lönnermark and Ingason [2]
A trailer mock-up with 3.1 ton corrugated paper cartons filled with plastic cups (19%), **Runehamar** test series, Test 4, u=3 m/s, A=50 m^2	70	1305	Lönnermark and Ingason [2]
A Leyland DAF 310ATi – HGV trailer with 2 tons of furniture, EUREKA 499, u= 3-6 m/s, A=25-35 m^2	128	970	Eureka report [3]
A trailer load with 72 wood pallets, Second Benelux tests, Test 14, u=1-2 m/s, A=50 m^2	25	600	Lemair et al [8]
A trailer load with 36 wood pallets, Second Benelux tests, Test 8, 9 and 10, u=0, 4-6 m/s and 6 m/s, A=50 m^2	13, 19 and 16	400, 290 and 300	Lemair et al [8]
A Simulated Truck Load (STL), EUREKA 499, u=0.7 m/s, A=25-35 m^2	17	400 ºC 10 m from the fire source	Eureka report [3]

The highest gas temperatures obtained are from the Runehamar test series and from petrol liquid fire tests in small-cross sections (<23 m^2). These fires resulted in gas temperatures in the range of 1200 – 1365 ^{o}C. These high temperatures are in agreement with the high levels of RWS and HC curves for tunnel fires as can been seen in Figure 2 where a comparison is made between the results of the Runehamar tests and different temperature-time curves for engineering design (ISO, HC, RWS, RABT/ZTG).

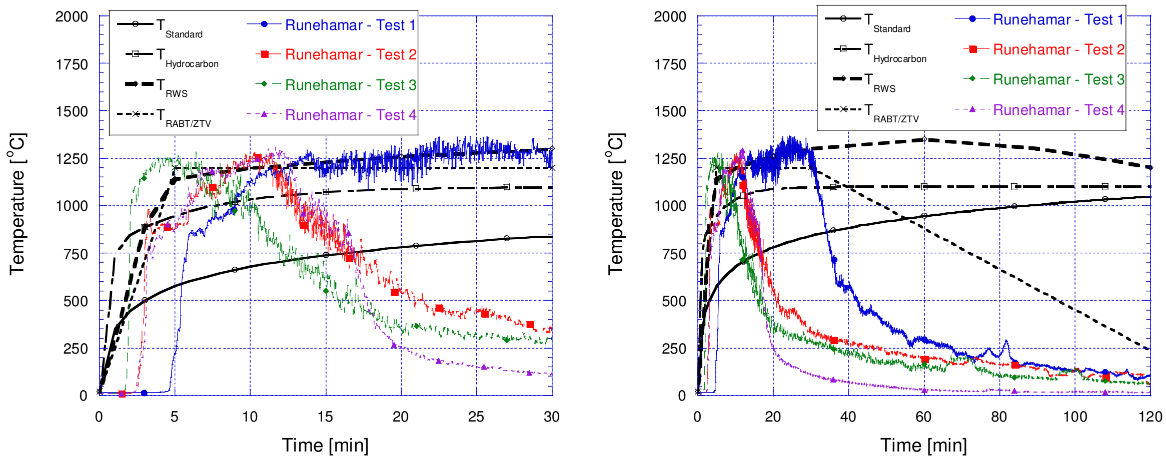

Figure 2 Comparison between the Runehamar tests and different temperature-time curves used by engineers. The graph to the left shows the first 30 minutes and the graph to the left the first 120 min [2].

In figure 2 (left graph) one can see that the gas temperatures from the Runehamar tests have steeper temperature rise than all the engineering curves presented although the RWS and HC curves comprises all the cases except for the furniture test (Test 3).

Table 4 Gas temperatures measured in large scale rail tunnel fire experiments

Type of vehicle, test series, test nr, u=longitudinal ventilation m/s	HRR (MW)	Peak gas temperature (^{o}C)	Reference
Rail			
A Joined Railway car; two half cars, one of aluminium and one of steel, EUREKA 499, u=6-8/3-4 m/s, A=25–35 m^2	43	980	Eureka report [3]
German Intercity-Express railway car (ICE), EUREKA 499, u=0.5 m/s	19	830	Eureka report [3]
German Intercity passenger railway car (IC), EUREKA 499, u=0.5 m/s	13	720	Eureka report [3]
Metro			
German subway aluminium car, EUREKA 499, u=0.5 m/s	35	1050	Eureka report [3]
German subway steel car, EUREKA 499, u=0.3 m/s	NA	680	Eureka report [3]

The results in Tables 3 and 4 show that there is a correspondence between high HRR and high temperatures but it appears to be also related to the type of fuel, fuel geometry, and size and cross-section of the tunnel. For high HRR ($\geq$35 MW) the gas temperatures become high ($\geq$900 ^{o}C), with exception of the tests in the Memorial tunnel test series with high ceiling height and 100 MW. This observation is applicable even when the ventilation rate is high

($\geq$3 m/s). This can be explained by the fact that for high HRR the flames impinge on the ceiling and the combustion zone, where the highest temperatures are usually obtained, is situated close to the ceiling, even when the longitudinal ventilation deflects the flames. All together these results indicate that the type of fuel, its geometrical shape and size, the tunnel cross-section, and the combustion efficiency are important parameters for the temperature level

4. CONCLUSIONS

The HRRs for single passenger cars (small and large) vary from 1.5 MW to 8 MW, but the majority of the tests show HRR values less than 5 MW. When two cars are involved the peak HRR vary between 3.5 and 10 MW. There is a great variety in the time to reach peak HRR. It varies between 10 and 55 minutes. The highest peak HRRs are obtained for the HGV trailers. It is found to be in the range of 13 to more than 200 MW depending on the fire load. The time to reach peak HRR is in the range of 10 to 20 minutes. The fire duration is less than one hour for all the HGV trailer tests presented.

The highest gas temperatures are obtained from HGV trailers and from petrol liquid fire tests in small-cross sections. These fires resulted in gas temperatures in the range of 1200 – 1365 ^{o}C. These high temperatures are in agreement with the high levels of RWS and HC curves for tunnel fires.

5. ACKNOWLEDGMENT

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